

Gigahertz-Peaked Spectrum Radio Sources

M. L. Lister

NRAO, 520 Edgemont Road, Charlottesville, VA, USA 22903

Abstract. The study of compact AGN which possess convex radio spectra (the gigahertz-peaked spectrum, or GPS sources) has generated a lot of interest over the last four decades, since these objects offer a unique opportunity to probe both the early evolutionary stages of relativistic AGN jets and their immediate nuclear environments. In this article I trace Ken Kellermann's early investigations of these sources, which played a major role in justifying the development of modern-day VLBI techniques. I describe how our understanding of these AGN has progressed since Kellermann's early discoveries, and discuss several ways in which the current classification scheme can be simplified to reflect intrinsic source characteristics, rather than observer-biased quantities. Finally, I discuss recent results from the VLBA 2 cm survey concerning the relativistic jet kinematics of the two-sided peaked-spectrum sources 4C +12.50 (PKS 1345+125) and OQ 208 (1404+286).

1. Initial discovery

The history of peaked-spectrum radio sources can be traced back to Ken Kellermann's graduate student days at the Owens Valley Radio Observatory in the early 1960s. At that time, the revised 3C catalog had just been published (Bennett 1962), and there was great interest in obtaining accurate broad-band radio spectra of these bright sources. For his Ph.D. thesis, Kellermann used the variable spacing interferometer at Owens Valley to obtain flux densities at four frequencies between 750 and 3200 MHz for 160 objects from the 3C list and other radio catalogs available at that time. Approximately half of the sample had straight, steep spectra consistent with incoherent synchrotron emission from a population of electrons having a power-law energy distribution.

The remaining radio sources had somewhat curved spectra, and two unusual objects: CTA 21 (0316+161) and CTA 102 (2230+114), had convex profiles that peaked around 900 MHz (Kellermann et al. 1962), hence the origin of the term "gigahertz-peaked spectrum" (GPS) sources. These two CTA objects had been discovered serendipitously by Dan Harris at Owens Valley several years earlier, and subsequently generated a great deal of excitement in the Soviet Union as possible beacons from extraterrestrial civilizations. Kardashev (1964) had argued that considering the effects of quantum noise and competing background emission, the most efficient spectral profile for transmitting radio signals across the galaxy was remarkably similar to that of CTA 21 and CTA 102. This coincidence fueled intense speculation as to their origin. The situation grew more

interesting when Sholomitskii (1965) reported highly unusual flux density variations in CTA 102 at 32 cm. This motivated Kellermann (1966) to look for “artificial” features as predicted by Kardashev (1964) in the spectrum of PKS 1934-638, but none were present.

Kellermann et al. (1962) had realized early on that the 3C sources with distinctly curved spectra had the highest brightness temperatures, but incorrectly attributed this to spectral ageing processes. Slysh (1963) was subsequently able to fit the curved spectra of 3C 48 (0134+329) and CTA 21 using formulae he derived for a synchrotron self-absorbed source, and calculated their angular sizes to be exceedingly small (140 and 10 milliarcsec, respectively). This led Shklovsky (1965) to reason, using his spherically expanding supernova model, that peaked-spectrum sources had to be quite young and should display substantial flux density variations over time.

At around the same time, Dent (1965) reported significant flux density changes in 3C 279, and Kellermann & Pauliny-Toth (1968) began to regularly monitor a sample of bright AGN at wavelengths ranging from 2 to 40 cm. They soon discovered that flux variability was quite common in flat-spectrum AGN, but virtually absent in the peaked-spectrum sources. This posed serious problems for Shklovsky’s simple spherical expansion model for AGN variability, which was later dropped in favor of more complex shock-in-jet models (e.g., Aller et al. 1985). Several groups, including Maltby & Moffet (1965), failed to confirm Sholomitskii’s discovery of variability in CTA 102, although later low-frequency observations of this source (e.g., Hunstead 1972) showed flux density variations that were probably associated with interplanetary scintillation.

1.1. Early VLBI observations

By 1966 there was overwhelming indirect evidence that many of the brightest radio-loud AGN were exceedingly compact. Both the high turnover frequencies of the peaked-spectrum sources and light travel time arguments applied to source variability suggested that some AGN could only be studied using very long interferometric baselines exceeding several million wavelengths. Kellermann (1964) had pointed out two years earlier that the peaked-spectrum sources were all intrinsically very luminous, and therefore could provide a number of good targets for very long baseline interferometry (VLBI).

These findings provided the scientific motivation for several groups around the globe to independently pursue the development of VLBI techniques. Early VLBI observations between Green Bank and Haystack in 1967 at a wavelength of 18 cm (Clark et al. 1968) showed that many AGN were still unresolved, which underscored the need for even longer baselines at shorter wavelengths. The following year, Kellermann et al. (1968) obtained the first inter-continental fringes of several AGN at 6 cm, between Green Bank and Onsala, Sweden. These fringe detections gave the first direct measurement of sizes 1 mas or smaller for several AGN, including the peaked-spectrum source 2134+004.

The direct confirmation of small source sizes using VLBI renewed a debate launched two years earlier by Kellermann (1966) in his analysis of the spectrum of PKS 1934-638: was the low-frequency spectral turnover in peaked-spectrum sources due to free-free absorption (FFA) by thermal plasma, or synchrotron self-

absorption (SSA) from relativistic electrons? Or was it related to the presence of cold plasma, as described by the Razin (1960) effect?

Surprisingly, this debate still continues nearly forty years later, with recent papers discussing either FFA (e.g., Bicknell, Dopita, & O’Dea 1997) or SSA models (e.g., Snellen et al. 1999). The main difficulty is that both models contain enough free parameters to fit virtually any convex spectrum, albeit with somewhat different constraints (see O’Dea 1998). Multi-frequency VLBI absorption studies (e.g., Marr, Taylor & Crawford 2001; Shaffer, Kellermann, & Cornwell 1999) may eventually settle this issue, but at present it remains plausible that both mechanisms play a role in creating the spectral turnovers in these sources.

2. Classification schemes

The standard view of peaked-spectrum sources today is that they are compact, powerful, young radio sources that reside in gas-rich environments at the centers of active galaxies (O’Dea 1998). Other typically quoted properties include low fractional polarization, low apparent jet speeds, and low flux density variability. However, in reality most individual peaked-spectrum sources display only some of these characteristics, and exceptions to the “classic” definition are unfortunately the norm.

Part of the problem is that the current definition is based only on the overall radio spectrum of an AGN, which is often the sum of many complex, time-variable emitting regions in a relativistic jet. The spectral shape can also be heavily influenced by the external environment, as in the case of FFA. It could be argued, therefore, that a peaked spectrum by itself tells us very little about an AGN, except for the obvious fact that it is dominated by an emitting region of small angular size. This suggests that the term “GPS” should either be abandoned entirely, or qualified in more detail so that it can be used as a true physical classification, and not solely a phenomenological one. Below I suggest some simple ways that the GPS classification could be modified so that it favors intrinsic rather than observer-biased properties.

2.1. “Masquerading” blazars

A first step toward a more definitive classification scheme would be to eliminate flat-spectrum, variable AGN (i.e., blazars) from the GPS class. What distinguishes the blazars from GPS sources is their bright, flat-spectrum cores, but in some blazars the signature of the core can be occasionally hidden in its integrated radio spectrum. Kovalev et al. (2002) have shown that the radio spectra of many blazars change dramatically with time, often showing remarkably GPS-like convex profiles during flux density outbursts. This can naturally be explained by the ejection of a new feature in the jet, whose individual self-absorbed spectrum briefly dominates the total radio flux. Many of the “high-frequency peakers” found by Torkinoski et al. (2001) appear to fall into this category.

A small fraction of blazars also display persistent features in their jets that often outshine the flat-spectrum core. These are likely associated with either stationary shocks or bends in the jet, and can give rise to a relatively stable, convex spectrum. In most cases, however, the signature of the flat-spectrum core can be found in another region of the spectrum, well away from the spectral

peak of the stationary component. A well-known example is the blazar 4C 39.25 (0923+392), which has a convex spectrum above 1 GHz, but a distinctively flat spectrum over the region $0.1 < \nu < 1$ GHz. Ironically, CTA 102 also shows the distinct flat-spectrum and variability of a blazar at frequencies above 3 GHz, and should be excluded from the GPS category. As it turns out, the only reason CTA 102 was originally called a GPS source is that it was discovered during a relatively inactive state when its spectrum happened to be convex.

In order to eliminate these “masquerading” blazars from the peaked-spectrum class, two additional restrictions should be imposed. First, a bona fide peaked-spectrum source should display a canonical convex spectrum that a) peaks at *any* radio frequency, and b) maintains this spectrum consistently at all epochs. A canonical peaked spectrum has been constructed by de Vries et al. (1997), and has $\alpha > 0.5$ for $\nu < \nu_m$, where $S_\nu \propto \nu^\alpha$ and ν_m represents the spectral turnover frequency. In the high frequency part of the spectrum well past the turnover where the source is optically thin, the spectral index is steeper than -0.5 .

2.2. Compact-steep spectrum sources

The current classification scheme is also complicated by the nebulous division between the GPS and compact steep-spectrum (CSS) sources. These are often grouped together based on their many shared characteristics (see the review by O’Dea 1998). For example, when plotted together on the intrinsic size vs. ν_m plane, they form a continuous trend having a single slope (size $\propto \nu_m^{-0.65}$; O’Dea & Baum 1997). The CSS sources originally got their name since they were unresolved with connected interferometers ($\theta < 1''$), and had overall steep spectra ($\alpha \simeq -0.7$). However, subsequent low-frequency observations of CSS revealed that many in fact had spectral turnovers at a few hundred MHz. The term GPS then became synonymous with sources with $\nu_m \simeq 1$ GHz, and those with lower frequency turnovers remained CSS sources.

This completely unphysical, arbitrary division generates additional redshift biases in “complete” samples of CSS and GPS sources, since it depends on the *observed* turnover frequency. Some authors (e.g., Fanti et al. 1985) have used an intrinsic size criterion of 1 kpc to divide CSS and GPS sources, but again this does not correspond to any physical quantity. Specifically, there is no evidence of a bi-modality in the observed size distribution. Instead, 1 kpc merely corresponds to the typical size of a source with a turnover frequency of 1 GHz. Furthermore, not all GPS/CSS have measured redshifts, making some size determinations impossible. To make matters worse, many intrinsically small GPS sources appear to have associated, large-scale emission, that is perhaps the result of past, episodic jet activity in the source (see review by Lara et al. 2002). It is unclear how to assign a characteristic size to these sources. Finally, there is again the issue of “masquerading” blazars, many of which tend to have small projected jet sizes due to foreshortening. These sources can display steep radio spectra if their flat-spectrum core is under-luminous compared to the jet. This appears to be the case for the superluminal CSS sources 3C 138 (0518+165), 3C 147 (0538+498), and 3C 216 (0906+430).

In light of these difficulties, the CSS classification should probably be reserved for physically small (< 20 kpc) sources that truly show no spectral

turnover down to the lowest observed frequencies. Some CSS might very well be foreshortened, but these should be re-classified as blazars if their viewing angles can be constrained, for example, by measurements of superluminal motion. Furthermore, any CSS that shows a MHz-frequency spectral turnover and has a stable, canonical convex spectrum should be combined with existing GPS sources under the blanket classification “peaked-spectrum radio source”.

2.3. Compact symmetric objects: a misnomer?

With the advent of hybrid imaging techniques for VLBI data in the early 1980’s, it became possible to further classify GPS and CSS sources on the basis of their parsec-scale morphologies. Phillips and Mutel (1980) popularized the “compact double” class on the basis of VLBI observations of CTD 93 (1607+268) and 3C 395 (1901+319), which showed bright lobe-like features separated by a few hundred pc. As the sensitivity of VLBI arrays steadily improved, more and more “double” sources were seen to have faint emission that connected the lobes to a weak core component. The term “compact double” was soon abandoned in favor of “compact symmetric object” (CSO).

Although the term CSO is now widely used in the literature, it is a somewhat misleading description of these sources. First, the word “compact” can have different meanings depending on the context. VLBI researchers tend to use this term to describe a source with a large VLBI-to-single dish flux density ratio (i.e. brightness temperature), whereas most other astronomers would take it to mean a physically small object. Indeed, most AGN that are classified as CSOs do satisfy both of these definitions, but a growing number of CSOs (and other peaked-spectrum sources as well) appear to be associated with kpc-sized regions of weak, extended emission (Stanghellini et al. 1998).

The “symmetric” part of the class definition is also problematic. Wilkinson et al. (1994) first introduced the term CSO to describe sources such as 2352+495, which possess a fairly high degree of morphological symmetry between their jet and counter-jet. However, the term CSO is now widely applied to *any* GPS source that shows two-sided VLBI jets, regardless of apparent symmetry. This is illustrated by many CSO candidates in the COINS sample of Peck and Taylor (2000).

The current definition of a CSO, then, relies solely on two properties: a GPS spectrum, and a two-sided VLBI jet morphology, with source compactness and symmetry playing insignificant roles. For the remainder of this article, therefore, I will drop the term “CSO” in favor of “two-sided peaked-spectrum source”.

3. Jet kinematics of two-sided peaked-spectrum sources

Since 1994, Kellermann and the VLBA 2 cm survey collaboration have been regularly monitoring a large sample of AGN in order to learn more about the kinematics and evolution of relativistic jets (Zensus et al. 2002). Although the goals of the program are mainly statistical, the sample also includes several peaked-spectrum sources which we are studying in closer detail. Here we report on two particularly interesting two-sided peaked-spectrum sources: 4C +12.50 (PKS 1345+125) and OQ 208 (1404+286). For the remainder of this paper

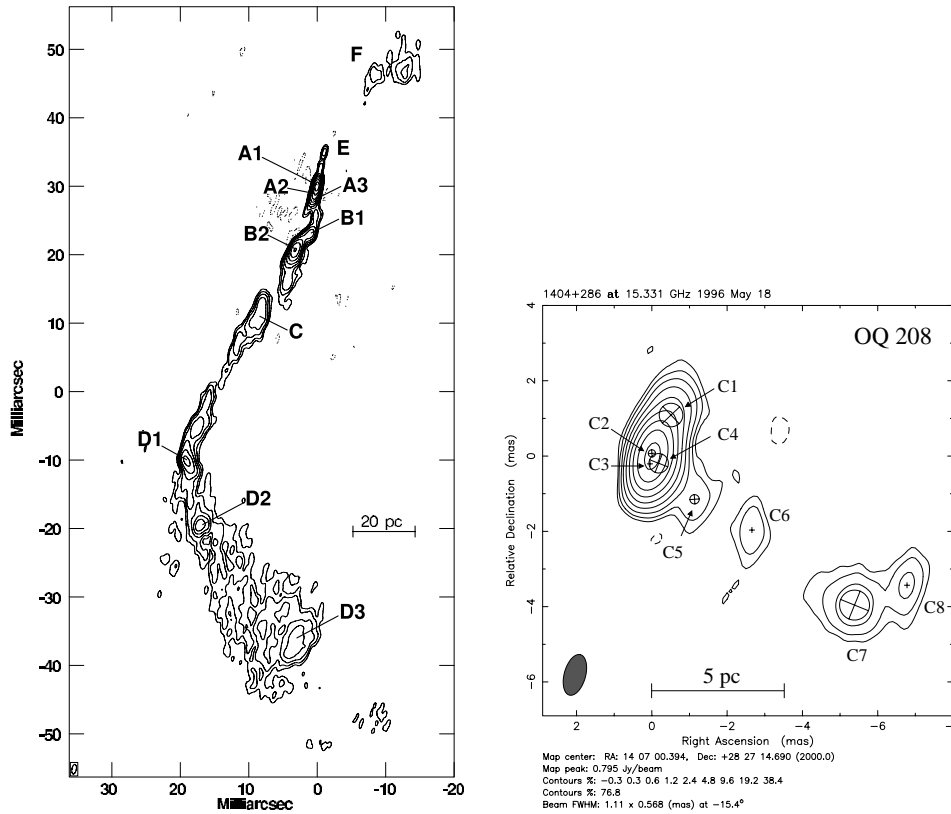


Figure 1. VLBA 2 cm images of 4C+12.50 (left panel; from Lister et al. 2003) and OQ 208 (right panel).

we assume an accelerating cosmology with $\Omega_\lambda = 0.7$, $\Omega_\lambda = 0.3$, and $H_o = 70$ km s⁻¹ Mpc⁻¹.

3.1. 4C +12.50

The powerful radio source 4C +12.50 lies within an ultraluminous infrared galaxy at $z = 0.12$ that is rich in both molecular and atomic gas. The host contains two optical nuclei separated by ~ 3.5 kpc that appear to have undergone a recent merger, as evidenced by its tidal tail structure and distorted isophotes (Gilmore & Shaw 1986). Our VLBA observations (Lister et al. 2003) reveal a well-defined jet structure with a total extent of ~ 100 mas = 220 pc (Fig. 1). The brightest feature in our full-track VLBA image (A1) has an inverted spectrum and was identified as the core by Stanghellini et al. (2001). Like most peaked-spectrum sources, the integrated polarization of 4C +12.50 as measured by the VLA is very low ($m < 0.2\%$), however, our analysis has revealed small regions with extremely high fractional polarization in the southern jet. These range up to $m = 30\%$ at the major bend (D1) and $m = 60\%$ at the very tip of the jet (D3). The electric vectors in both regions are nearly perpendicular to the total intensity contours.

We have detected two components in the southern jet (A2 and A3) that display substantial apparent motion over our five year sampling interval. Their mildly superluminal speeds ($\simeq 1.2$ c) and the presence of the bright northern counterjet suggest that the jet axes of 4C +12.50 lie fairly close to the plane of the sky. We obtained a good fit to the overall bent morphology of the jet and counter-jet using a simple constant-wavelength helix of opening angle 23° projected at 82° to the line of sight. Although some helical jets are the result of material being ejected ballistically from a precessing nozzle (e.g., SS 433; Hjellming and Johnston 1981), this is not the case for 4C +12.50, as there is ample evidence for streaming of material along the curved ridgeline of the jet. These include the alignment of the polarization gradient and inferred magnetic field vectors along the jet ridgeline, and the highly polarized flux at specific points in the jet (i.e., the major bend and southern tip). These features can naturally be explained as shocks in the flow that have ordered the magnetic field of the jet. The helical ridge line is likely the result of growing Kelvin-Helmholtz instabilities (e.g., Hardee 1987) that are driven by a small precession of the jet nozzle. Such a precession might be expected for the black hole of a galaxy such as this one that has undergone a recent merger event.

The relativistic speeds of the inner jets are significantly higher than the outer lobe expansion speeds measured for other two-sided peaked-spectrum sources ($v/c \simeq 0.3$ c; Owsianik, Conway & Polatidis 1999). The southern lobe is too diffuse to determine an accurate advance speed, but if it is typical of other sources, this implies that a significant amount of jet kinetic energy must be dissipated over a relatively small distance (~ 200 pc). This is perhaps being channeled into the large expansion of the jet at D1 or a terminal shock at D3.

3.2. OQ 208

The radio source OQ 208 is associated with the broad line Seyfert 1 radio galaxy Mrk 668, which like 4C +12.50, shows signs of tidal distortion (Stanghellini et al. 1993). Being one of the closest known peaked-spectrum sources ($z = 0.077$), we are able to study its jet kinematics with high spatial resolution (1 mas $\simeq 1.5$ pc). Its radio structure is very compact, with $> 99\%$ of its cm flux originating from a region with a projected diameter of ~ 12 pc (Fig. 1). Aaron (1996) discovered a faint component ~ 33 mas SW of this region at position angle -107° . All of the parsec-scale structure lies within a large diffuse halo of diameter ~ 30 kpc (de Bruyn 1990).

We have assembled ten individual VLBA epochs at 2cm from the VLBA 2 cm survey and other programs that span the time period 1995-2001. For the purposes of our proper motion analysis, we have modeled the inner jet structure using eight discrete circular Gaussian and delta-function components labeled C1-C8 in Fig. 1. The precise location of the center of activity in this source is not well known. Our analysis shows the distance between C1 and C5 is shrinking at a rate of $54 \mu\text{as y}^{-1}$ ($v/c = 0.28$), which immediately rules out the possibility of the core being in the eastern region. Component C6 lies roughly halfway between the eastern and western “lobe” structures, and is a logical candidate for the core. However, the distance between C6 and the eastern structure is increasing at rate of $\sim 180 \mu\text{as y}^{-1}$, while the distance from C6 to the western structure is *decreasing* by $140 \mu\text{as y}^{-1}$. If we assume there are no inward motions,

the core must lie between C5 and C6, with C6 representing a jet feature that is moving to the SW.

We are unable to determine any individual component velocities without a stationary reference point, however, C3 and C7 are separating at a rate of $60 \pm 4 \mu\text{as y}^{-1}$. If OQ 208 has been steadily expanding at this rate, its parsec-scale emission is only $\sim 1100 \pm 73$ years old. This is typical of kinematic ages derived for other two-sided peaked-spectrum sources (Owsianik et al. 1999).

4. Summary

Since Ken Kellermann's initial discoveries regarding gigahertz-peaked-spectrum sources nearly forty years ago, these powerful radio sources have greatly increased our understanding of active galaxies. They not only provided strong incentive for the development of modern-day VLBI techniques and synchrotron emission theory in compact radio sources, but are now being used to confirm the scenario by which AGN jet activity is triggered by galactic mergers. Unfortunately, the exposure of GPS sources to the larger astronomical community has been somewhat hindered by a complex and awkward classification scheme. However, with the small modifications discussed in this article, it should be possible to implement a scheme that distinguishes GPS sources on the basis of intrinsic, physical properties, and not observer-biased ones.

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